

Electromagnetic Pumps for Conductive-Propellant Feed Systems

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Prototype electromagnetic pumps for use with lithium and bismuth propellants were constructed and tested. Such pumps may be used to pressurize future electric propulsion liquid metal feed systems, with the primary advantages being the compactness and simplicity versus alternative pressurization technologies. Design details for two different pumps are described: the first was designed to withstand (highly corrosive) lithium propellant, and the second was designed to tolerate the high temperature required to pump liquid bismuth. Both qualitative and quantitative test results are presented. Open-loop tests demonstrated the capability of each device to electromagnetically pump its design propellant (lithium or bismuth). A second set of tests accurately quantified the pump pressure developed as a function of current. These experiments, which utilized a more easily handled material (gallium), demonstrated continuously-adjustable pump pressure levels ranging from 0-100 Torr for corresponding input current levels of 0-75 A. While the analysis and testing in this study specifically targeted lithium and bismuth propellants, the underlying design principles should be useful in implementing liquid metal pumps in any conductive-propellant feed system.

I. Introduction

METALLIC propellants have been used in almost all major categories of electric propulsion (EP) devices. Ion, Hall, and MPD thrusters have demonstrated high performance with metallic propellants (using mercury or cesium, bismuth and lithium, respectively). There is presently a renewed interest in liquid metal propellants for use in high-power nuclear-electric propulsion systems. For example, NASA is currently developing lithium-fed MPD thrusters¹ and bismuth-fed Hall thrusters.² An important element of these projects is the development of a propellant management systems (PMS) capable of precisely metering the propellant flowrate. Aside from the obvious, functional necessity for a reliable PMS in the thruster system, the ability to accurately control and measure the propellant flow rate is necessary in order to assess the performance of the thrusters. Flight hardware will have the added demands of high reliability and low system mass.

A primary component of any PMS is the pressurization system, which is used to force liquid metal from the reservoir into the thruster. In the present work we describe our efforts to develop compact, robust electromagnetic (EM) pumps for pressurization of liquid lithium and bismuth feed systems. We first review the current state of the art (SOA) in liquid metal feed systems, EM pumps, and associated technologies. Next, we place the present work in context by defining the specific requirements for current electric propulsion systems. We then describe our general approach and give specific design details. The experimental apparatus is described and test results are summarized. Lastly – drawing on the results – we comment on the suitability of the devices developed in this study for application in future EP feed systems.

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II. Review of Current State of the Art

A. Liquid Metal Feed Systems

Since the 1960s, there have been many different EP applications in which a liquid metal has been used as the propellant source. In these various applications the propellant is typically delivered in liquid form either to A) a high temperature vaporizer (temperature controlled atomization) or B) an emitter tip immersed in a high electric field (field ionization controlled atomization). We proceed with a review of the different techniques that have been employed to control liquid metal mass flow rate to a vaporizer.

1. Passive Control

Liquid metal propellants can be controlled passively using surface tension and the capillary forces that naturally arise. For any wetting propellant the capillary forces act to move the liquid metal into smaller cross-sectional area channels without any moving parts. In addition, there are no components in the system that preclude it from operation at elevated temperatures. The maximum possible flow rate and pressure head at the vaporizer are fixed in this type of system and for simple geometries these can be computed based upon the channel dimensions and the surface tension properties of the given liquid.³

Surface tension driven systems have been used quite extensively in EP. Cesium ion thrusters appear to have been the first to employ this type of propellant management system for a liquid metal.⁴⁻⁶ Ion thrusters employing single capillary channels or porous tungsten 'sponges' which 'wick' the propellant from the reservoir and transfer it to the vaporizer have both been operated. More recently, capillary forces have been used for propellant management and delivery in cesium⁷ and indium⁸ field emission electric propulsion (FEEP) systems.

2. Active Control

Variable force can be applied to liquid metals using a number of different techniques allowing for active control over the propellant flow rate and/or pressure force exerted by the liquid metal on a vaporizer plug. In EP devices, active propellant management has been accomplished using:

1. elastic diaphragms,
2. metallic bellows or pistons,
3. electromagnetic pumps,
4. direct propellant vaporization.

In No. 1, an elastic diaphragm separates the propellant reservoir into two sections, one containing the liquid metal propellant and the other initially evacuated or at low pressure. A variable and controllable force is exerted upon the propellant by increasing the gas pressure in the latter section. The gas pressure may be increased by using a pressure-regulated gas supply or by using heat to vaporize a compound and expand the resulting gas (e.g., frozen CO₂ or liquid freon). As the pressure exerted by the gas increases and propellant is displaced from the reservoir and pushed towards the thruster. This technique works well for propellants like mercury where the temperature levels in the reservoir are not too high. However, the diaphragm can melt if this technique is attempted for a propellant with a high melting point.

Conceptually, metallic bellows and pistons operate in much the same way as the elastic diaphragms. The bellows forms a propellant reservoir which decreases in size as the bellows is contracted. This contraction forces the propellant out of the reservoir and towards the thruster. A piston is pushed using an electric motor and simply contracts the space by translating into the propellant tank. These approaches are especially applicable to the control of high temperature liquid metal propellants, but there is a mass associated with the use of motors and the reservoir volume change will occur as a series of 'steps' instead of a smooth, continuous transition.

Electromagnetic pumps exploit the fact that liquid metals are conducting fluids capable of carrying current. By orienting an applied magnetic field perpendicular to a current passing through the liquid metal, a $\mathbf{j} \times \mathbf{B}$ Lorentz force is exerted on the fluid. This has the effect of either accelerating the propellant as it passes through the electromagnetic pump or increasing the pressure head the fluid exerts at the thruster

vaporizer. Electromagnetic pumps can operate at elevated temperatures, but temperature limits can be reached if the applied magnetic field is produced using permanent magnets.

Finally, propellant can be vaporized in the reservoir and then allowed to migrate towards the thruster. This method is simple and robust owing to the lack of mechanical components in the system. It is considered active in that there can be no propellant mass flow without the application of heat. This technique does not offer a high degree of controllability in the mass flow rate making it difficult to obtain accurate thruster performance measurements.

Elastic diaphragms primarily appear in the EP literature in conjunction with mercury ion engines.^{9–11} Unlike in the cesium ion engines previously discussed, passive capillary control cannot be used when working with mercury since it is a non-wetting fluid.

Propellant management systems using metallic bellows or pistons typically appear in the literature for thrusters operating on liquid lithium. The bellows system was employed during the 1960s on MPD arc-jets.^{12,13} More recently, a piston-controlled lithium feed system (illustrated in Fig. 1) has been operated in conjunction with a Lorentz force accelerator.^{14,15}

Electromagnetic pumps have not been operated as the primary propellant feeding mechanism. They have, however, been used in conjunction with elastic diaphragm systems in mercury ion engines.^{9–11} In these systems, the EM pump acted as a mechanism to adjust the mercury pressure head at the vaporizer. One such pump produced a pressure differential of 0.6 atm when operating at a current level of 20 A.¹⁰

In laboratory experiments the direct vaporization technique has been used to feed propellant from a propellant reservoir to a thrust chamber. Experiments have been performed using a TAL-type Hall thruster in which bismuth vapor was fed in this manner.¹⁶ More recently a lithium Lorentz force accelerator used an open-ended heat pipe design to vaporize and feed gaseous lithium to the thruster.¹⁷

B. Current State of the Art

Several of the liquid metal feed systems previously described qualify as the current state of the art. Capillary-fed cesium ion thrusters and FEEP systems have either achieved flight-ready status or have successfully flown in space. Also, mercury ion engines employing elastic diaphragms have flown on such missions as SERT 1 and 2. Unfortunately, the non-wetting characteristics of liquid lithium and bismuth preclude us from using the capillary feed mechanism and the high melting temperatures eliminate the possibility of using an elastic diaphragm.

The piston driven propellant management system^{14,15} currently represents the state of the art for controlling a hot liquid metal propellant like bismuth or lithium (see Fig. 1). Propellant mass flow rate can

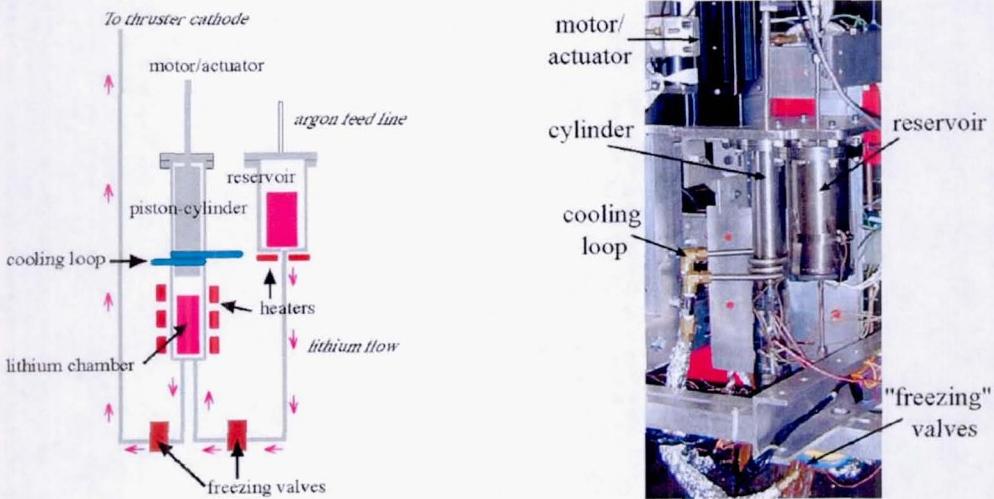


Figure 1. Schematic (left) and photograph (right) of the Princeton piston-driven lithium feed system (from Ref.¹⁴).

be measured by monitoring the propellant tank volume that the piston sweeps out over a given time. This technology is still at the research level of readiness.

Electromagnetic pump technology⁹⁻¹¹ may also be considered at or near the current state of the art. It has the advantage of possessing no moving parts. However, the technology readiness level is slightly below the piston driven system as EM pumps have not been used as the primary control component in a propellant management system and have not been used in conjunction with high-temperature liquid metal flows on the small scale being considered for electric propulsion applications.

C. Electromagnetic Pumps

The idea to use interacting currents and magnetic fields to pump a conducting fluid was first introduced by Michael Faraday and was later pioneered by Jack Northrup. Much effort was placed into the fundamental development of electromagnetic pump technology in the mid-1950s¹⁸⁻²⁰ and practical implementations of the idea were rapidly developed for use in nuclear reactor cooling systems.^{21,22} This is, to date, still the application in which the technology is most widely deployed.²³ Additional uses for electromagnetic (EM) pumps include the movement and control of seawater, molten metals, and various other conducting liquid metals employed in laboratory research.

For propellant control in electric propulsion applications, EM pumps possess several advantages over conventional mechanical pumps. They have no moving parts, thus eliminating mechanical friction losses and the need for bearings and seals. This is especially advantageous if the propellant is highly reactive (for example: lithium). Pump performance is controlled by adjusting the input current and, as a result, control can be executed with a high degree of fidelity over the entire pump operating range. These pumps are reliable, possessing no parts that are particularly failure-prone, and can be scaled to small sizes. As such, EM pumps should prove well suited as flow controllers in electric propulsion feed systems.

Many methods using electromagnetic forces for pumping have been devised, but four designs have become commonly used²⁴ (three of these are illustrated schematically in Fig. 2). They are the direct-current pump, alternating-current pump, flat linear induction pump (FLIP), and annular linear induction pump (ALIP).

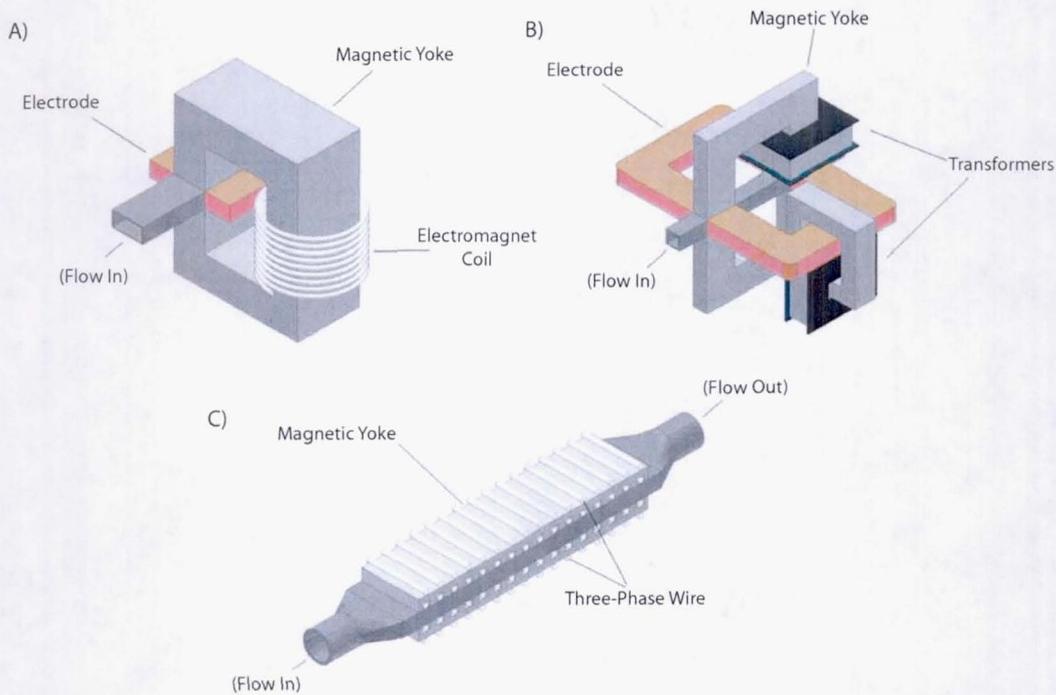


Figure 2. Conceptual schematics illustrating: A) a direct-current conduction pump, B) an alternating-current conduction pump and C) a flat linear induction pump (FLIP).

The FLIP and ALIP have only minor differences, so for the sake of brevity we shall restrict discussion to the FLIP.

In the direct-current pump (Fig. 2A), a perpendicular current and magnetic field interact to yield a Lorentz body force on the conducting fluid which acts perpendicular to both (i.e. streamwise $\mathbf{j} \times \mathbf{B}$ force). This pump is referred to as a conduction pump because the current is introduced into the conducting fluid through two electrodes which are in direct contact with the fluid. The magnetic field is conducted into the pump via a magnetic yoke and can be created using either permanent magnets or an electromagnetic coil. Direct-current conduction pumps are typically small and are well suited for laboratory experiments or applications requiring low flow rates.

The alternating-current pump (Fig. 2B) operates on the same basic principle as the direct-current pump in that and applied current and magnetic field result in streamwise pumping of the fluid. The primary difference is that the direction of the current flow oscillates as a function of time. Consequently, electromagnets must be employed so that the polarity of the magnetic field can also oscillate in a manner such that it remains in phase with the current. Typically, transformers built into magnetic yokes are employed. The use of transformers allows for greater power conditioning capabilities. Although the alternating-current pump is versatile and widely used for low-flow rate applications, it does possess several disadvantages. Since the current is time-varying, the efficiency is decreased by eddy currents which are induced in the pump and connecting wires. Eddy current losses increase rapidly with size, limiting alternating-current conduction pumps to small sizes and applications. In addition, losses can occur due to skin effect. These pumps are also 'noisy' since the pressure driving the fluid is continuously varying.

Although conduction pumps possess many desirable qualities, they also present three significant problems that can seriously degrade performance. These are:

- Current conduction through the walls of the channel,
- Current fringing at the electrodes,
- Armature effects.

A number of design strategies have been found to minimize these problems. The amount of current bypassing the fluid and flowing through the channel walls, and hence performing no work, can be minimized by constructing the channel using a highly resistive material, such as stainless steel.²⁵ The problem can be eliminated completely through the use of an insulating material. Examples of potential insulator materials are macor and aluminum nitride.

Current fringing occurs near the electrodes and becomes a serious issue when the current spreads out so far that it flows around the region in which the magnetic field is located instead of through it. When this occurs, the current does not interact with the magnetic field and no body force is produced. One potential solution to this problem is to install insulating baffles near the electrode edges on both the upstream and downstream sides.²⁶ The resistance these baffles present to the current can significantly decrease the fringing and increase pump efficiency. A second solution involves the use of chamfered magnets,²⁷ which would produce their own fringing magnetic field to encompass and interact with the fringing current.

Armature effects occur as the current passing through the conducting fluid creates its own magnetic field. This additional magnetic field increases the magnetic flux density present on the upstream end of the pump and decreases the flux density on the downstream end. The non-uniform magnetic field introduces a non-uniform electromagnetic body force and, consequently, a non-uniform pressure distribution. This effect can significantly lower the efficiency of the pump. The armature effects can be countered by varying the gap between the permanent magnets, with the upstream ends of the magnets spaced further apart than the downstream ends. This will help to balance the strength of the combined magnetic field. The precise amount of variation necessary to compensate for armature effects is an area that requires further investigation.

A flat linear induction pump (FLIP) is illustrated schematically in Fig. 2C. This differs from the previous two pumps (conduction pumps) in that the current in the conducting fluid is induced by a travelling magnetic field. To accomplish this, an alternating current is passed through sets of wires wrapped around iron cores. The time-varying current induces a magnetic field which passes through the conducting fluid. Currents are induced in the fluid which attempt to exclude the penetrating magnetic field. The induced currents and magnetic fields interact to yield a Lorentz force. A FLIP fluid channel typically possesses a long width and a short height and copper bars can be installed on the edges of the channel to provide a low resistance return path for the current for increased efficiency. The FLIP is usually employed in situations which require high

flow rates. High pump efficiencies can be obtained by using conducting fluids with a low resistivity, such as sodium. The temperature limits on the insulation on the wires supplying the driving current limits the temperatures at which a FLIP can operate.

The primary conclusion of the above review is that there has been no previous direct application of EM pumps and flow sensors in lithium and bismuth feed systems for electric thrusters. However, much germane information can be garnered from previous studies. In particular:

- EM pumps have been successfully implemented in mercury ion engine feed systems. This experience provides a general basis for EM pump designs; however, the direct implementation of the mercury pump design is impossible due to the radically different thermal and corrosive characteristics of lithium and bismuth, which demand completely different materials and sealing technologies.
- Liquid lithium EM pumps have been successfully implemented in nuclear reactor heat exchangers. However, the volume flow rates in these systems are many orders of magnitude higher than is required for propulsion applications. Furthermore, component mass and electrical efficiency were secondary issues in the design of nuclear system, whereas these issues are very important for propulsive applications.

III. Engineering Design

A. Definition of the Problem

The engineering problem associated with implementing EM pumps has two facets. First the pump must be capable of generating a sufficient pressure drop to cause the propellant to flow to the thruster at the design flow rate. Second, the pump must be constructed of materials that can contain the propellant of interest at elevated temperatures.

The pressure drop in a laboratory thruster feed system derives primarily from gravity (i.e., the pressure required to displace a column of propellant vertically from the reservoir to the thruster) and the vaporizer. In a typical thruster, pressurization of $\mathcal{O}(10^3)$ Pa is required to maintain fluid flow. Also, it is desirable that the fluid flow be stable, to avoid flow-rate oscillations inside the thruster that could adversely impact performance.

Material compatibility is a major issue in the design of lithium and bismuth feed system components. The corrosive nature of lithium severely limits the choices of fabrication materials. The problem is compounded by the fact that different lithium-compatible materials with electrically insulating and electrically conductive properties must be identified. In addition, a method to join the insulating and conducting materials without introducing liquid leaks into the system must be found. Bismuth is much less reactive than lithium, but it does destructively alloy with certain metals, such as copper. To maintain a liquid state, lithium feed system components must be heated to $\sim 200^\circ\text{C}$, while bismuth systems operate at $\sim 300^\circ\text{C}$. While these temperatures do not pose a problem for most metallic materials of interest, the elevated temperature levels do preclude the use of certain attractive insulating materials, such as plastics.

B. General Approach

Based on the background review and specific requirements enumerated above, we committed to the following general approach for electric propulsion EM pump development:

- Electric propulsion feed system EM pumps should be of the DC conduction variety. This type of pump provides the most compact solution, and simplifies the electrical design. The unsteady currents in AC conduction pumps are avoided, which could result in pulsating flows and mechanical vibrations that may complicate thruster performance measurements.
- A ceramic body should be implemented in the electromagnetic pump design to keep the current from by-passing the fluid and conducting through the channel walls. Also, high temperature (rare earth) permanent magnets should be used instead of magnet coils, since the physical dimensions of the pumps in our application will be relatively small. This will further enhance the electrical efficiency of the pump.

C. Analysis

The first part of the EM pump design process is theoretical analysis to determine the magnitude of the relevant parameters which yield a specified level of pump performance. An idealized schematic of an EM

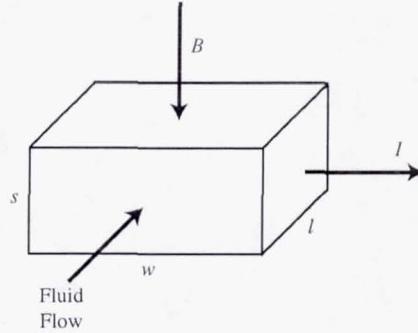


Figure 3. Idealized schematic of an electromagnetic pump.

pump is presented in Fig. 3. The liquid metal flows though a channel of width w , length l and height s . The magnetic field B and current I are perpendicular to the flow (and each other) and are uniform over the indicated faces.

The EM pump exerts a Lorentz body force F on the fluid in the direction of the flow when current flows between the electrodes, through the fluid. This establishes a pressure gradient in the fluid in the direction of the flow. The force can be written as

$$|\mathbf{F}| = \int \mathbf{j} \times \mathbf{B} d^3x,$$

where \mathbf{j} is the current density (equal in magnitude to $I/(l s)$ if $|\mathbf{j}|$ is uniform). Performing the integration yields

$$F = \frac{I}{l s} B l s w = I B w.$$

The force causes a fluid pressure drop to develop which is equal to

$$P = \frac{F}{s w} = \frac{I B}{s}. \quad (1)$$

We observe from Eq. (1) that the pressure drop is a function of the pump height, magnetic field strength, and total current. In Fig. 4a, pump pressures computed using Eq. 1 are plotted versus the parameter B/s . In practice, the maximum value of B/s that can be achieved is $\mathcal{O}(10)$. In addition, current levels above ~ 100 A should be avoided to limit Ohmic heating losses in a real system. We see that this effectively limits the pump pressure that can be developed to about 1 atmosphere. As stated earlier, the propulsion application will require $\mathcal{O}(10^3)$ Pa, which the analysis above shows is feasible with an EM pump.

The main energy loss mechanism in the pump is Ohmic dissipation (Joule heating) in the electrodes. Figure 4b shows computed levels of Joule heating for a 1 cm long tungsten electrode as a function of current and electrode cross-sectional area. We see that Ohmic losses are $\mathcal{O}(1)$ W, which is negligible compared to other thruster feed system components (such as the vaporizer).

Two final quantities of interest are the hydrodynamic Reynolds number (Re) and the magnetic Reynolds number (Re_m). These quantities are plotted in figures 4c and 4d over a range of flow speeds that are consistent with the bismuth and lithium mass flow rate requirements. Re is shown for several values of hydraulic diameter (D_h). The low value of Re indicates that flow in the pump will be laminar. The magnetic Reynolds number will also be small for both propellants, implying that the flow will not convect magnetic field lines downstream (that is, the magnetic field will not be “frozen” into the fluid).

D. Design Details

To accommodate the individual idiosyncrasies of lithium and bismuth, the design of the prototype EM pumps were somewhat different; therefore, we discuss the design of each pump separately, below.

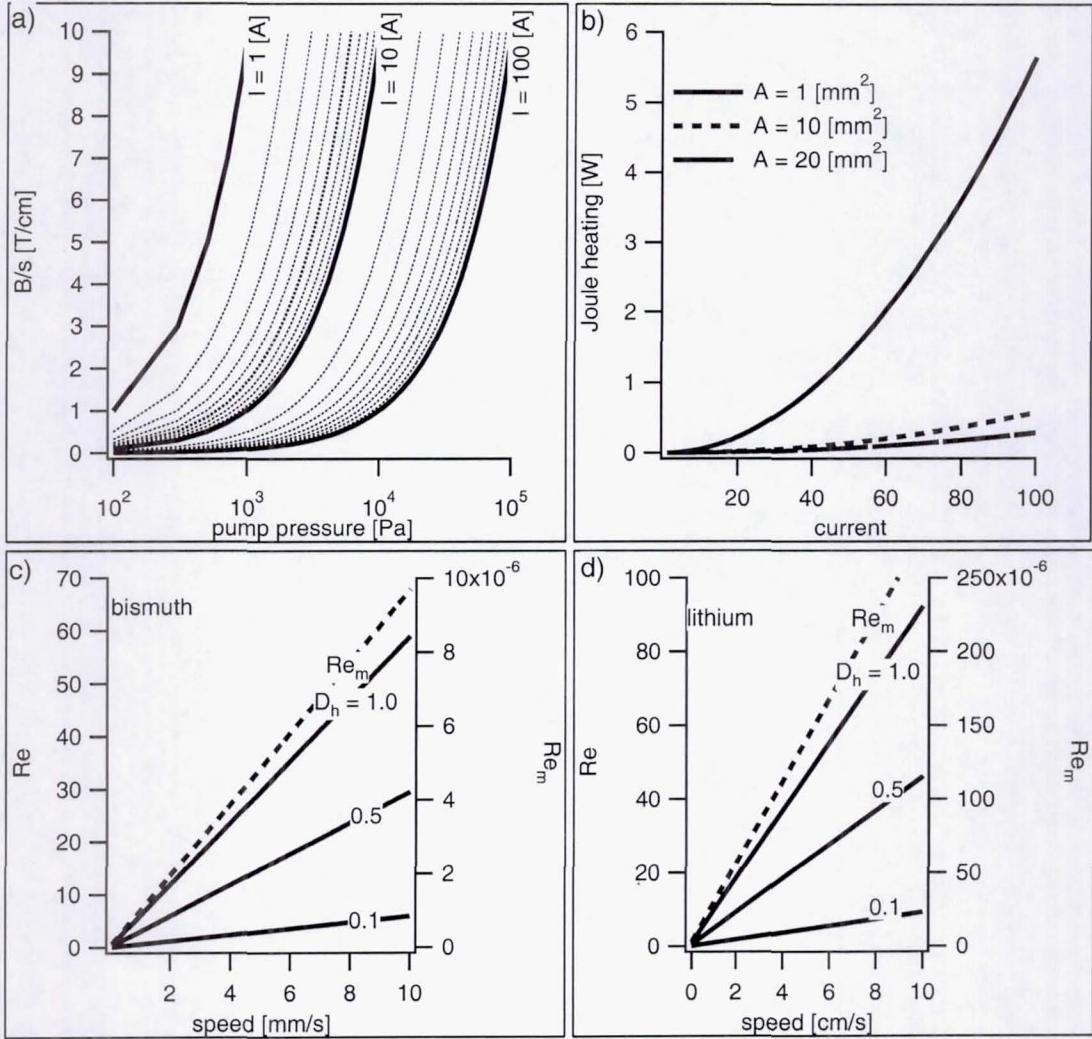


Figure 4. EM pump theoretical analysis plots: a) B/s ratio versus pump pressure at varying current levels, b) Electrode Joule heating versus pump current, Reynolds number and magnetic Reynolds number versus flow speed for bismuth (c) and lithium (d).

1. Lithium EM pump

The previous analysis showed that the current required to attain a given pump pressure decreases for greater values of B/s . However, there are practical limits on the maximum attainable value associated with the materials used to construct EM pumps. We chose to fabricate the central body of the prototype lithium EM pump from a ceramic insulating material to minimize stray conduction losses. The brittle nature of ceramic materials led us to choose a conservative value of s to minimize the potential for cracking. To our knowledge, we are the first to attempt to use an insulating material in an alkali metal EM pump.

From our review of the literature, the only insulating material that can also survive the corrosive nature of a lithium environment is aluminum nitride (AlN). Unfortunately, AlN is extremely difficult to machine, requiring expensive specialized diamond tooling. Another major pump fabrication issue was the method by which metallic electrodes and liquid feed lines are joined to the ceramic body. The problem is made worse by the fact that the interface must be hermetically sealed to avoid liquid leaks. One option that we investigated was the use of an “active braze” technique to bond the metallic parts directly to the ceramic body. Further investigation revealed that there is considerable uncertainty as to how well braze materials

would resist the corrosive effects of a lithium environment. For our materials, brazing is also quite expensive. An alternative option was to use metallic o-ring seals. Implementation of this option costs about ten times less than brazing.

Ultimately, we fabricated a lithium EM pump using the following materials: AlN body, tungsten electrodes, 316L stainless steel liquid feed lines, samarium cobalt magnets, an iron yoke, and Inconel o-ring seals (compression gaskets). A CAD solid model of the complete EM pump is shown at the top of Fig. 5. In this prototype design, the magnet separation was conservatively chosen to be fairly wide (6.4 mm) to minimize risk of insulator cracking in the active region of the flow channel. The B/s for the prototype configuration is ~ 1 , but could be increased to ~ 5 in future (but perhaps less robust) designs. The yoke, electrodes, and feed line end caps were designed to also serve as a means for compressing the o-rings. Photographs of the complete EM pump assembled and disassembled are shown at the bottom of Fig. 5.

2. Bismuth EM pump

Bismuth is much less corrosive than lithium, so the primary practical design constraint is the availability of high-temperature materials and, in particular, the material that can be used for the (insulating) pump body. Teflon and other thermoplastics cannot withstand the $\sim 300^\circ\text{C}$ required to keep bismuth in the liquid state. We chose to use glass-mica ceramic (also known as macor) because it is stable at liquid bismuth temperature

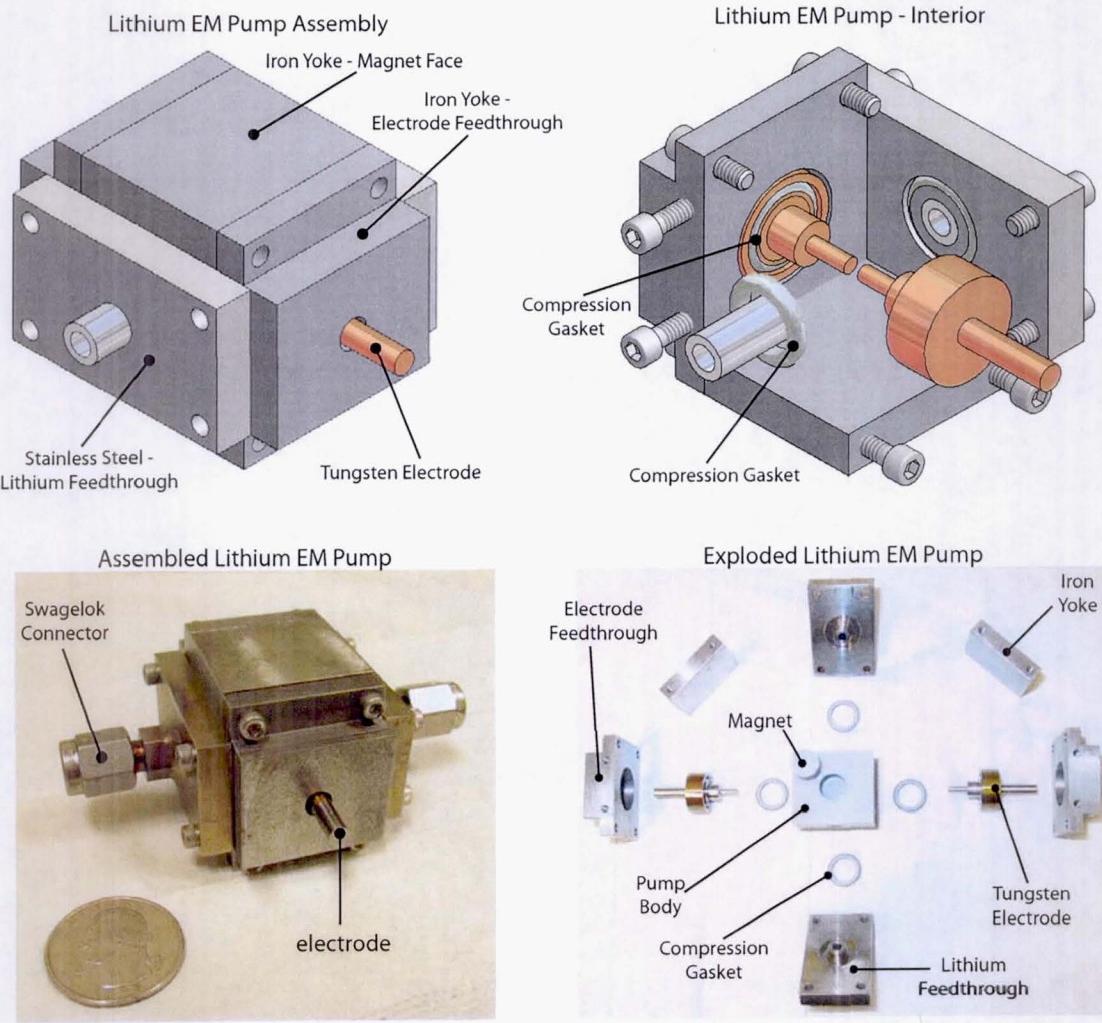


Figure 5. Lithium electromagnetic pump CAD model and photographs.

levels; it is also relatively inexpensive and easily machined.

The ease of fabrication afforded by the use of macor (versus aluminum nitride) allowed us to pursue a more aggressive design for the bismuth EM pump. Samarium cobalt magnets were again chosen, but the magnet separation and channel height was considerably smaller (magnet separation = 2.9 mm and $s = 2.3$ mm), which yielded an on-axis magnetic field strength of ~ 0.4 Tesla and $B/s \sim 2$.

The major components of the prototype bismuth EM pump are shown in figure 6. The CAD model at the top of the figure shows a sectioned view that reveals the inner construction. The materials used to fabricate the pump were: macor (pump body), iron (magnet yoke), 316L stainless steel (end caps and feed lines), Paraflour (TM) (o-ring seals), Inconel (electrodes), and samarium cobalt (magnets). The magnets were separated from the flow channel by a thin layer (~ 0.3 mm) of macor. The electrodes were bonded to the macor body using high-temperature epoxy. The feed lines were welded to the end caps and sealed to the macor body using high-temperature o-rings. The feed lines utilized Swagelok VCR fittings for attachment to the rest of the feed system.

IV. Test Apparatus

A. Open-loop Test Apparatus

Two types of experiments were conducted to demonstrate the operation of the EM pumps. The first experiments were qualitative, proof-of-concept tests that simply aimed to show that each device could contain

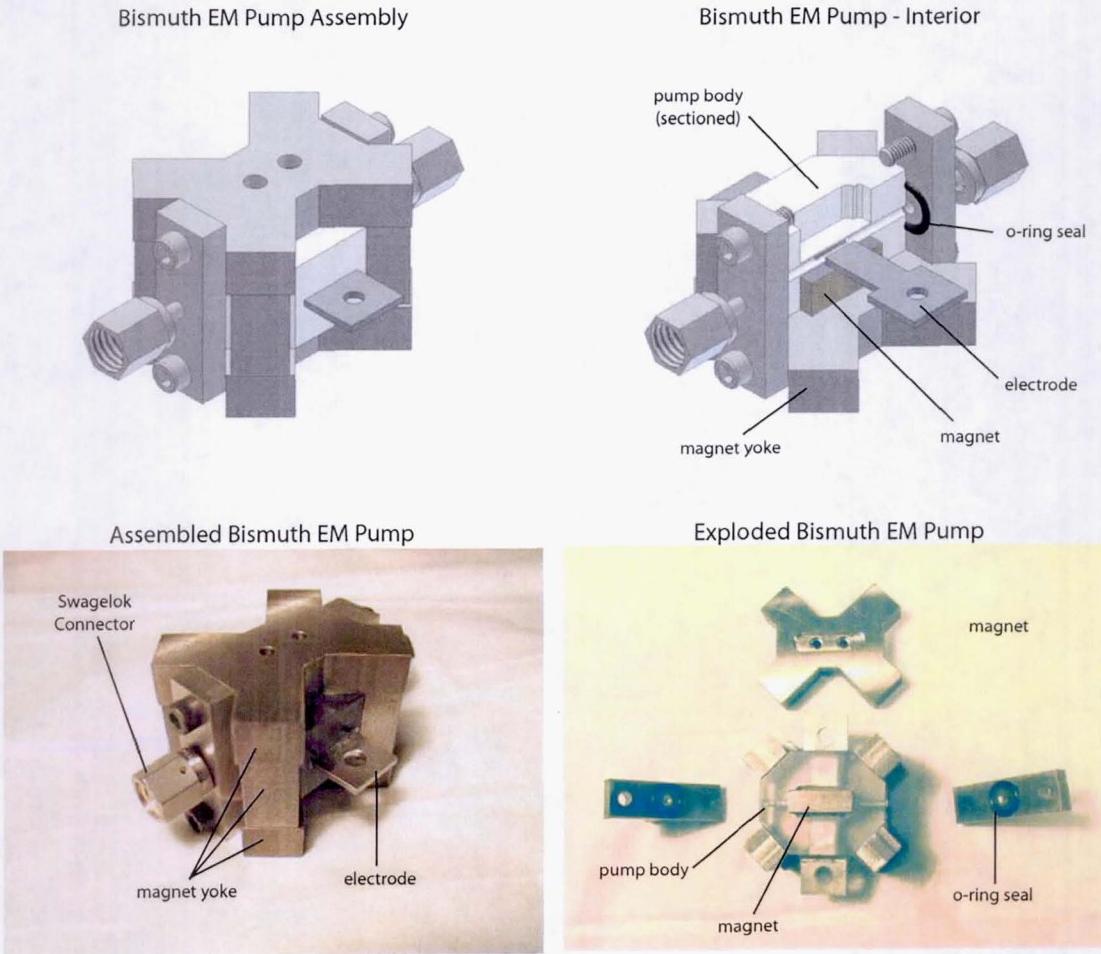


Figure 6. Bismuth electromagnetic pump CAD model and photographs.

liquid metal at the required temperature level and electromagnetically pump it from a reservoir into a catch basin. The open-loop apparatus for these experiments is shown in Fig. 7. In both the lithium and bismuth tests the EM pumps were situated above the reservoir in order to encourage draining (due to gravity) of the feed lines back into the reservoir at the completion of a test run. Consequently, to begin testing, the reservoirs had to be pressurized (using argon) in order to 'prime' the pumps. The gas pressurization line for the bismuth reservoir is visible in Fig. 7.

The open-loop tests were conducted inside a vacuum chamber in order to minimize convective heat losses from the system. Vacuum testing is also mandatory for lithium, as it will (in liquid state) spontaneously combust in when exposed to air.

B. Pressure Measurement Apparatus

A test apparatus was constructed to facilitate direct, quantitative measurement of the EM pump pressure as a function of applied current. In order to eliminate the hazards and difficulties associated with handling liquid lithium and bismuth, these tests were conducted using a substitute liquid metal – gallium. Since the pressure developed by an EM pump is independent of the particular properties of the liquid (see Eqn. 1), the results of the pressure tests are generally valid for any conducting fluid, including lithium and bismuth.

The most obvious way to measure the fluid pressure drop across an EM pump is to use the pump to displace fluid inside a closed container (of fixed volume) which also contains a cover gas. Displacement of the fluid will change the gas volume inside the container, and the concomitant gas pressure change can be accurately measured using a gas pressure transducer and correlated with the induced EM pump pressure. Unfortunately, at the low pressure ranges of interest, the pressure drop associated with the vertical displacement (against gravity) of a dense fluid can be comparable to the change in gas pressure. So, to get an accurate measurement of the pump pressure, the change in height of the fluid in the container must also be measured with high precision. To avoid the necessity of measuring both pressure and fluid height, an EM pump pressure measurement scheme was devised that makes use of two reservoirs; the approach requires simultaneous measurement of gas pressure in the two reservoirs, but not fluid column height.

A schematic illustration of the principle of operation of the EM pump pressure measurement apparatus is shown in Fig. 8. The bottoms of two reservoirs are connected by an EM pump. Both reservoirs are partially filled with an electrically conducting fluid. The pressure in each (sealed) reservoir is measured using a pressure transducer. The pressure in the second reservoir can be controlled by opening a valve between the reservoir 2 and a high pressure gas bottle.

The progression of events required to measure the EM pump pressure is illustrated by a hypothetical example in Fig. 8b. Initially (time t_0) the fluid in each reservoir rests at its equilibrium position, with the initial gas pressure in each reservoir being P_{10} and P_{20} , respectively. At time t_1 a fixed, steady current is applied to the EM pump and fluid begins to flow from reservoir 1 into reservoir 2. As fluid flows out of reservoir 1, the gas volume increases and the pressure goes down; the opposite effect occurs in reservoir 2. At some time t_2 the system reaches a new equilibrium and fluid flow ceases. If at a later time t_3 a gas valve

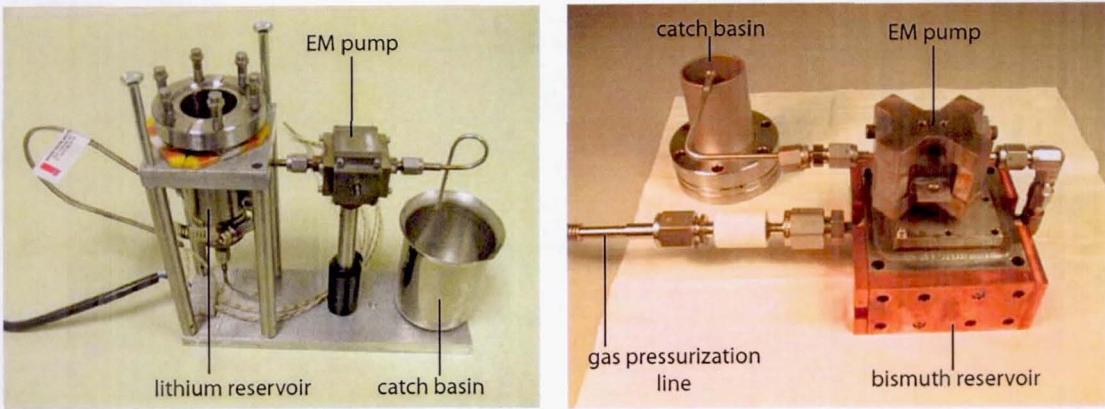


Figure 7. Open loop test apparatus for lithium (left) and bismuth (right).

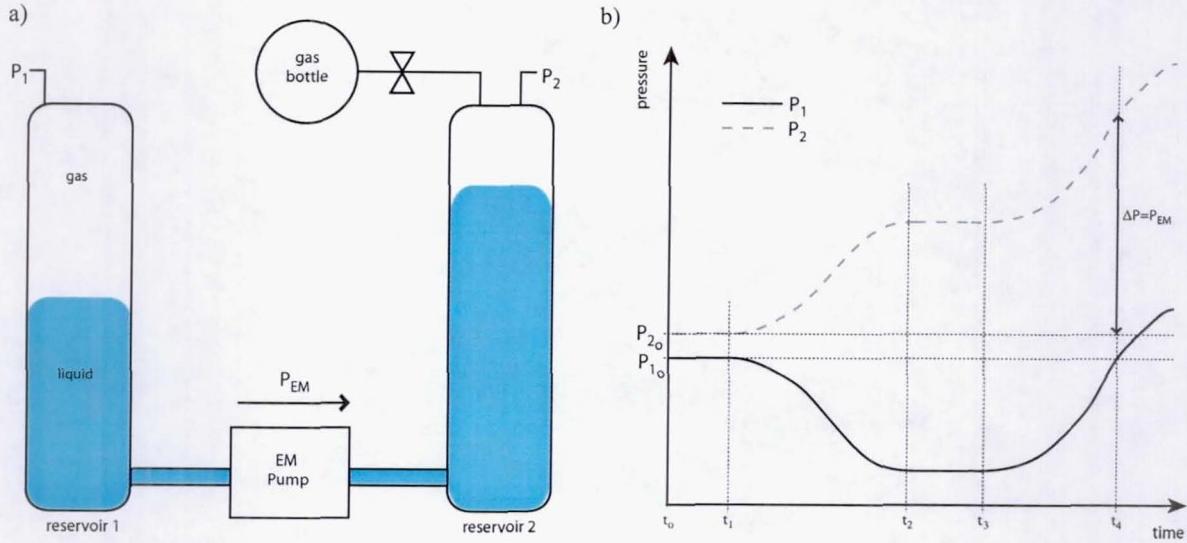


Figure 8. Schematic illustrations of EM pump pressure measurement methodology: a) schematic of test apparatus components and b) notional plot of hypothetical experimental data.

is opened to increase the pressure in reservoir 2, the fluid will be forced from reservoir 2 back into reservoir 1. At some later time t_4 , enough fluid will be forced back into reservoir 1 to return its cover gas to its initial pressure P_{1o} ; at this point the fluid in each reservoir will have returned to their initial equilibrium positions. With the influence of fluid column height re-balanced, the excess pressure in reservoir 2 is solely due to the EM pump:

$$\Delta P = P_{14} - P_{1o} \quad . \quad (2)$$

A test apparatus was constructed (see Fig. 9) to implement the EM pump pressure measurement strategy described above. In addition to the components illustrated in Fig. 8a, a pressure equalizing valve was added. This valve connected the tops of the two reservoirs, which allowed the same initial pressure to be established in both reservoirs (i.e., $P_{1o} = P_{2o}$).

V. Experimental Results

A. Open-loop tests

1. Lithium Tests

Approximately 100 g of lithium was loaded into the reservoir of the test apparatus shown in Fig. ??a. When the reservoir thermally stabilized to ~ 300 K and the EM pump temperature stabilized at ~ 250 K, 15 Torr of argon pressure was introduced into the reservoir using the GPS to prime the pump. After the electrodes in the pump were electrically bridged by lithium, the pump current was set to 20 A. Lithium flow (at a rate of ~ 1 g/sec) commenced and liquid droplets were expelled into the catch basin (see the left panel of Fig. 10). The EM pump was exposed to flowing lithium for approximately 100 sec during a test run.

Aside from demonstrating electromagnetic pumping with lithium, we also sought to validate the compatibility of our pump materials with the corrosive lithium environment. After the test run, the pump was disassembled and inspected. No evidence of material degradation was observed (see the right panel of Fig. 10). No cracking or corrosion of the AlN body was visible and no lithium was evident outside of the o-rings, indicating successful sealing. The metallic components of the pump also appeared to be undamaged.

2. Bismuth Tests

Similar open loop results were obtained with bismuth.

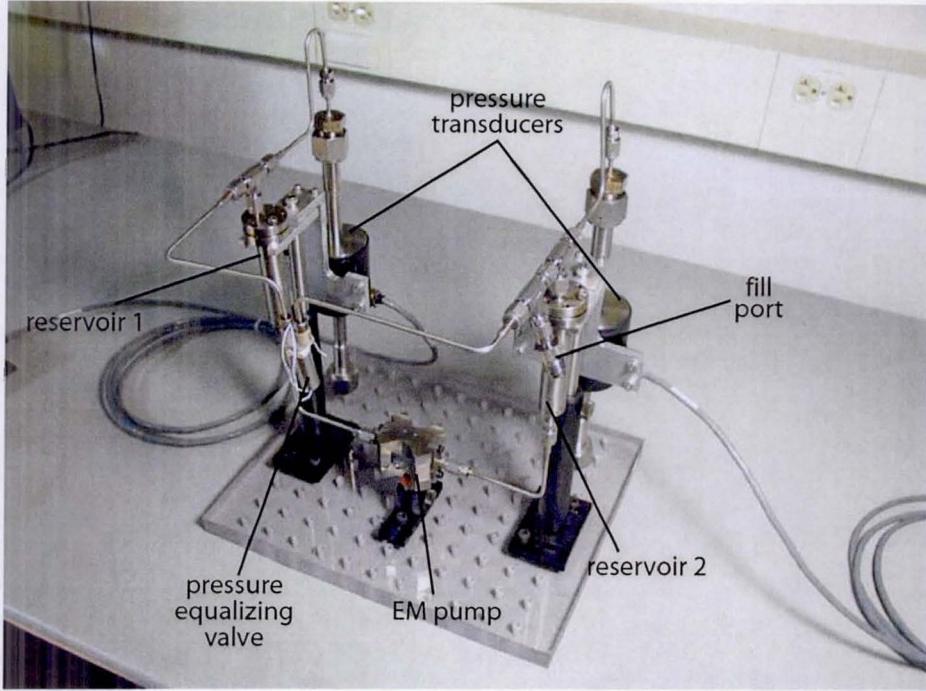


Figure 9. Open loop test apparatus for lithium (left) and bismuth (right).

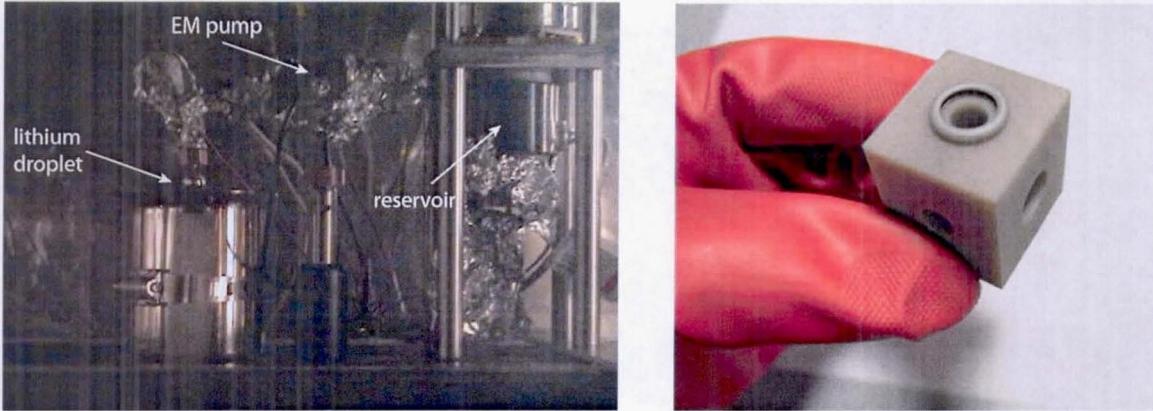


Figure 10. Photographs of (left) lithium EM pump test apparatus during operation and (right) EM pump post-test inspection.

More detail will be added here later.

B. EM Pump Pressure Measurements

EM pump pressure measurements were obtained using the test apparatus shown in Fig. 9. Applied current levels ranging from 10-70 A were tested. The data shows that the bismuth EM pump develops higher pressure for a given current level, compared to the lithium EM pump. This is expected, since the B/s ratio is greater in the bismuth EM pump design. The data is seen to be very linear, and quantitatively in agreement with the theoretical predictions shown in Fig. 4a.

More detail will be added here later.

VI. Summary and Conclusions

The following major results are reported in this study:

- We chose to base our EM pump designs around central, insulating ceramic bodies, which was a departure from all earlier liquid metal EM pump work.
- Lithium material compatibility was a principal issue, which led us to design our EM pump around an aluminum nitride body. A conservative EM pump design was engineered, and the complete device was fabricated and assembled. Tests with hot lithium flowing through the EM pump were conducted. Subsequent disassembly of the pump revealed no degradation of the stainless steel feed lines, tungsten electrodes, or aluminum nitride body. We considered both brazing and metal o-rings as possible solutions for sealing the EM pump metal components to the aluminum nitride. O-rings were much more cost effective, so they were implemented in the prototype EM pump design. The four o-ring seals showed no signs of leaking after tests were conducted with liquid lithium.
- High-temperature material compatibility was a driving design issue for the bismuth EM pump. Macor was chosen for the insulating body material, which initially allowed for a higher performance pump design (versus the lithium pump design). High-temperature o-rings were used to seal the feed lines to the macor body. Tests with hot flowing bismuth successfully demonstrated operation of the pump; post test inspection revealed no problems.
- Quantitative measurements of EM pump pressure were acquired for both the lithium and bismuth EM pump. The results were in agreement with the theoretical design predictions.

By proving the functionality of EM pumps for application in EP liquid metal feed systems we have established a strong basis from which a complete lithium or bismuth feed system can be built.

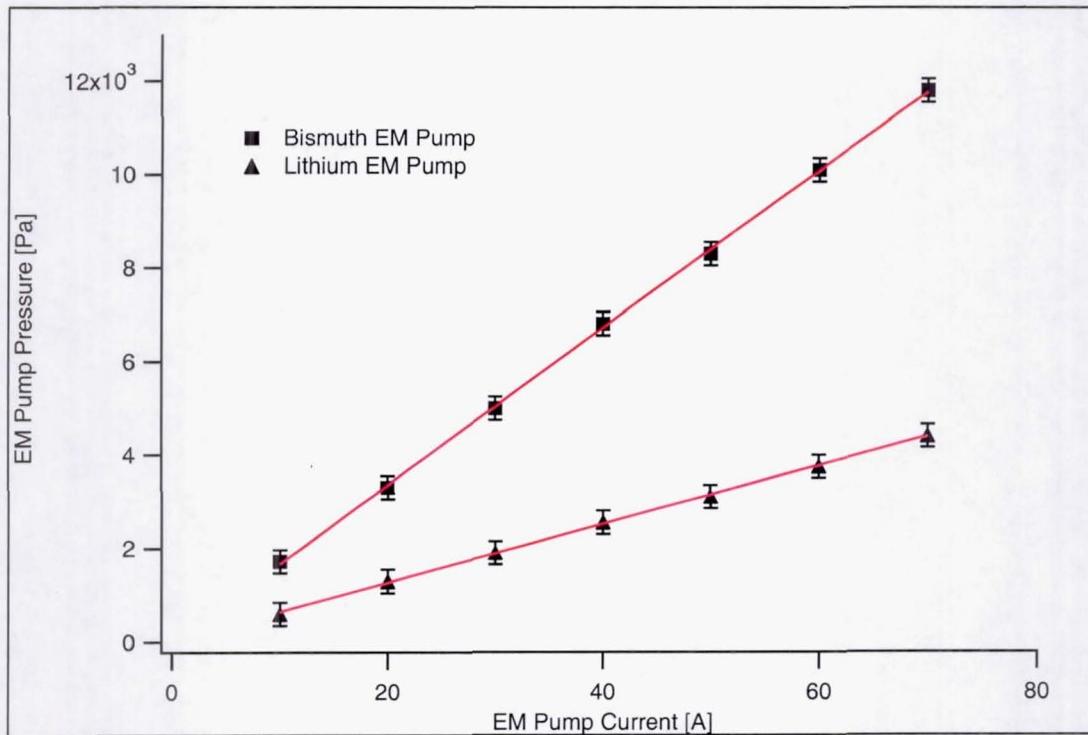


Figure 11. EM pump pressure measurements (pressure versus current for lithium and bismuth EM pumps).

VII. Acknowledgements

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Electromagnetic Pumps for Conductive-Propellant Feed Systems

IEPC-2005-295

*Presented at the 29th International Electric Propulsion Conference, Princeton University
October 31 – November 4, 2005*

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Prototype electromagnetic pumps for use with lithium and bismuth propellants were constructed and tested. Such pumps may be used to pressurize future electric propulsion liquid metal feed systems, with the primary advantages being the compactness and simplicity versus alternative pressurization technologies. Design details for two different pumps are described: the first was designed to withstand (highly corrosive) lithium propellant, and the second was designed to tolerate the high temperature required to pump liquid bismuth. Both qualitative and quantitative test results are presented. Open-loop tests demonstrated the capability of each device to electromagnetically pump its design propellant (lithium or bismuth). A second set of tests accurately quantified the pump pressure developed as a function of current. These experiments, which utilized a more easily handled material (gallium), demonstrated continuously-adjustable pump pressure levels ranging from 0-100 Torr for corresponding input current levels of 0-75 A. While the analysis and testing in this study specifically targeted lithium and bismuth propellants, the underlying design principles should be useful in implementing liquid metal pumps in any conductive-propellant feed system.



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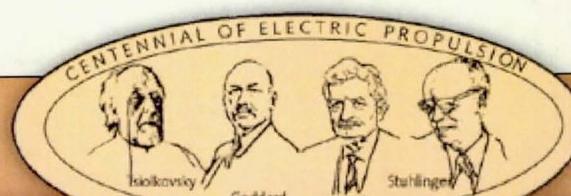
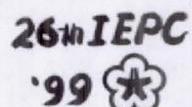
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